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US Army Corps
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Waterways Experiment
Station

Proceedings, Workshop on Prediction of Groundwater Flow into Deep Tunnels and Excavations

18-19 February 1987

by Richard E. Goodman, Anders Bro, editors
Geotechnical Laboratory

Prepared for Headquarters, U.S. Army Corps of Engineers

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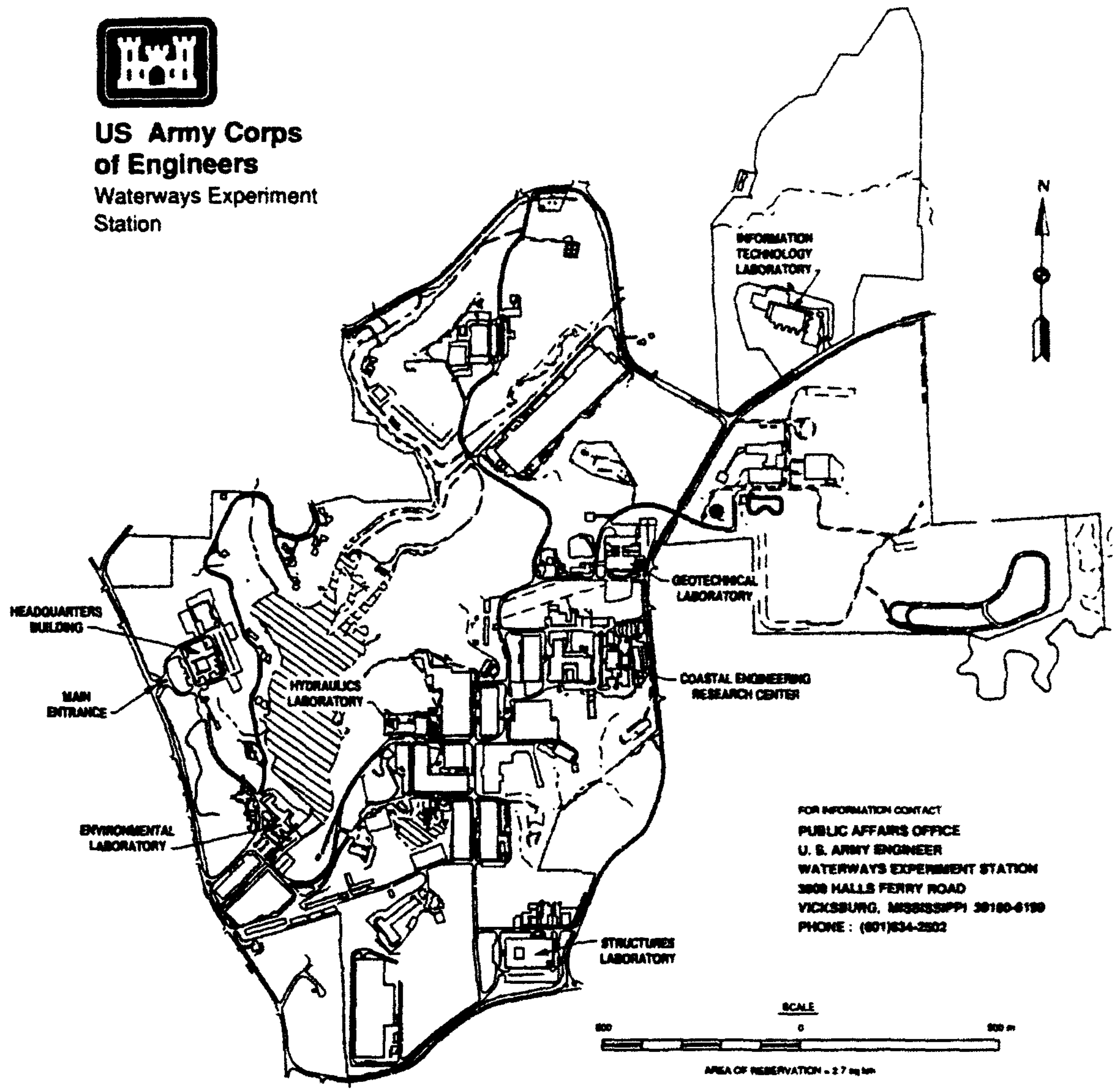

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CONTENTS

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This conference is dedicated to Mr. Paul Fisher who was the driving force behind investigating the problems due to groundwater in deep bases. U.S. Army Engineer Waterways Experiment Station, in particular Dr. Don C. Banks and Mr. Jerry S. Huie, are thanked for initiating and supporting the conference.

We greatly appreciate the generosity of the participants who devoted personal time and resources to participate in the conference. The participants contributed their knowledge, understanding, and experience in the field of water flow in underground works. Thanks are also due to Mr. Rick Sisson for logistical planning and recording the conference.

We would also like to acknowledge the funding agencies who made this conference possible: the U. S. Army Corps of Engineers, The Defense Nuclear Agency, and the U. S. Air Force Ballistic Missile Office.

PREFACE

The workshop proceedings reported herein were conducted for the U.S. Army Engineer Waterways Experiment Station (WES).

The Principal Investigator was Dr. Wendell O. Miller, Rock Mechanics Branch (RMB), Soil and Rock Mechanics Division (S&RMD), Geotechnical Laboratory (GL), WES. The workshop proceedings were written by Dr. Anders Bro and Dr. Richard E. Goodman, University of California at Berkeley.

Supervision at WES was provided by Mr. J. S. Huie, Chief, RMB. The project was conducted under the general supervision of Dr. D. C. Banks, Chief, S&RMD; and Dr. W. F. Marcuson III, Director, GL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

1 Purpose of the Conference

At the time of the conference, a deep underground base was a viable alternative for basing strategic defense systems. Among many of the questions that needed to be considered in establishing the suitability of such a basing system was how water would impact the survivability of the base. A hypothetical geology was proposed (Generic Mountain "C") which was analyzed by a number of private companies and individuals. A consensus was generally reached that the model contained inconsistencies, thus leading to several revisions. Although analyses of water flow were done, there seemed to be little confidence in their estimates and it became evident to practical tunnelers that a closer look at predictive techniques was required.

This conference was therefore convened to draw together a group of authoritative people in the field of flow modelling to establish and document the problems encountered with water in tunnelling and the difficulties in modelling underground flow, and to discuss the gamut of predictive techniques. The results of this conference are discussed in these proceedings. In short, experience indicates that encounters with significant water inflows are unpredictable. Most modelling efforts have been performed using homogeneous models; this cannot result in reliable predictions of flows in any given short section of tunnel. Some current efforts directed toward modelling flow probabilistically seem promising. Most of the case studies and field experiences focused on the transient flows that are encountered during initial excavation. Although these flows are certainly important with regard to the economy of construction, they may not be relevant to long-term seepage into an underground base, which would be of greater concern to the deep basing community. Despite this slight shift in focus, the material presented at the conference was revealing and suggests some directions of research that could be productively pursued.

In summary:

a. The focus of this report is on the analysis and prediction of water flow into deep underground excavations in rock. It does not address remedial measures that could be taken to stem water inflows.

b. Geologic uncertainties and variability inherent in fracture characteristics (the fracture locations, apertures, extents, etc.) lend little confidence to flow predictions.

c. Where these uncertainties can be reduced, numerical techniques can be used to predict flows as a function of time.

d. In light of these inherent uncertainties, statistical and probabilistic techniques are being developed to assess geological data, to statistically model flow, and to quantify the confidence of flow calculations.

e. Further work is needed to refine current analytical techniques used for interpreting basic hydrologic data (field test data).

f. Statistical simulation methods look promising and should be continued, perhaps with a goal of predicting actual flows and the probability of encountering such flows, in addition to the current goal of studying the flow behavior of fracture systems.

g. The phenomenon of flow channeling needs to be addressed. The impact that channelling has on the flow magnitudes, the localization of flow, and the variability that channeling introduces needs to be investigated.

2 Summary of Presentations and Noteworthy Comments Made During the Presentations

This section highlights the most important aspects of the presentations and comments made by the attendees during the presentations. These comments are gleaned from the tape recordings and notes taken during the conference.

Day 1

Richard E. Goodman

Professor Goodman set the stage for the conference by introducing the problems that have been encountered due to water flowing into underground excavations. He proceeded to suggest the conditions under which one is apt to find water, and proceeded to present the analyses that he and others had done in the 1960s. The analyses are covered in his paper[1] (included in Appendix A).

His experiences, as expounded upon in his presentation, were that the ability of engineers to properly model water flow in realistic settings is very poor and that there is little hope of doing it accurately. John Gibbons suggested that this inability may be due to the lack of skill to properly characterize the discontinuous rock mass.

One of the other comments that Professor Goodman made that seemed to be echoed throughout the conference was that the most important concentrations of water were at faults. Faults act both as aquitards and aquifers since water is able to flow along them (on one side or the other, or in the fault itself), but is less able to flow across them.

He also highlighted the unique problems associated with specific rock types, notably the large flows that occur in karst. (Lynn Brown related experiences obtained in the African Gold fields of Dreifontein[2,3], reviewed in Section 3, and Bill Meneley summarized some of his experiences in the Potash Mines in Canada, discussed later in this section. Another problematic rock is basalt with its very closely fractured nature.

The structure of the rock plays an important role in the role of water flow. It has been Professor Goodman's experience that water is often focused in geologic synclines and areas of tensile fractures where the rock is open jointed creating a fractured reservoir.

Professor Goodman recommends that a solution to the flow of water into deep underground excavations be solved through a detailed consideration of engineering geology rather than through mathematical modelling.

Tor Brekke

Professor Brekke's presentation emphasized the problems that develop as a result of water flows into excavations. Specifically, he addressed the flow of water into the Balsam Meadows Project in the southern part of the Sierra Nevada Mountains in California. In this case history, the fractures were expected to be closed since the same joint set in nearby projects (Helms and Kerckhoff[2]) was tight. In fact, at Balsam Meadows, the fracture apertures at depths were about 6 in. This finding is an example illustrating that fractures do not necessarily become tighter with depth.

However, Professor Brekke indicated that joints generally do tighten with depth, in particular in more ductile rocks such as schists. These can be expected to yield tighter fractures with correspondingly lower flow rates than more brittle rocks such as granite.

He also suggested that seismic activity can stimulate water flows. In the Clayton silver mine in Idaho, water inflow rates increased 250 percent following an earthquake. John Gibbons suggested that the increased flow might be due to increased connection in the flow system. Professor Brekke referenced Nick Barton in saying that shear movements increase fracture flow. This last reference is also corroborated by the work of Margaret Asgian[4,5] in which computer modelling has supported this hypothesis.

Professor Brekke also pointed out other deleterious effects of water. With increasing depth, the rock and ground water temperature may increase to a point where it reduces worker productivity and possibly requires remedial measures. Cold water has an equally debilitating effect.

Professor Brekke was skeptical that water flows could generally be satisfactorily stopped using grout. The experience from Helms was that extensive grouting, using superfine cement, reduced the water inflows by 40 percent.

It was Professor Brekke's opinion that no one can accurately predict the magnitude and locations of flows into a tunnel.

David Rogers

Mr. Rogers gave accounts of several projects in which excessive volumes of water flowed into tunnel workings[6]. His experience is that one can not make any generalizations in predicting water flows even in the same geologic units, as a single rock unit may contain a variety of joint spacings and apertures.

He reiterated Professor Brekke's point that tunnelling from the dry side of a fault that is acting as an aquitard toward the hanging wall can be dangerous. Penetrating an impervious partition (a partition between ground water compartments) can result in sudden water inflows accompanied by large volumes of rock debris.

Mr. Rogers emphasized the need for sufficient geological investigations and referenced case histories in which problems might have been avoided with more extensive investigations. He cited the use of feeler holes to detect water in underground workings and the use of subsidiary tunnels to handle very large water inflows.

The rock types that predominantly constitute aquifers are basalt, fractured chert and siltstone, gravel, volcanic ash, and rhyolite. Mr. Rogers suggested water flows may be driven by thermal gradients as well. Thus, the regional flow regime may be substantially influenced by the presence of hot water, as may have been the case in the Tecolote tunnel near Mono Lake, California.

The primary conduits of underground water are the fractures. Thus, any analyses should concentrate on the fractures. One of Mr. Rogers conclusions (from his PhD work at Berkeley[7]) is that conductive fractures are generally more closely spaced in more brittle rock than in ductile rock. Also, in a given rock type and formation, the joint spacing increases with increasing bed thickness. Mr. Rogers has laboratory data that indicate that rocks with large post-fracture-stiffness (the "stiffness" of the stress-strain curve after peak load has been obtained) tend to exfoliate easily and have closer joint spacings than rocks with lower post fracture stiffnesses. Along the same line of estimating fracture spacing, his experience has been that thin beds that have been folded tend to be less fractured than thick folded beds.

He also emphasized the need to consider three dimensional aspects of water flow, and to account for biological activity in analyzing water flow. He gave an example in which the flow under a dam declined as a result of deposition of diatom skeletons (induced by an increase in salinity of the water held behind the dam). Mineral deposition and solution could also play a role in respectively decreasing or increasing water flow rates. (See the summary of Mr. Meneley's presentation later in this section.)

Tom Doe

Mr. Doe's presentation related to techniques for predicting water flows in a rock mass and into an underground excavation. He concentrated mainly on the statistical nature of water flow and how to develop data that could be used to develop a probabilistic analysis.

The distribution of joint apertures and extents are highly skewed to the low end; the majority of the joints are spaced closely together and the extent of most joints is not particularly great. But since flow varies with the cube of the joint aperture, the flows through the wide and extensive fractures govern the flow through the whole system. Thus, the flow regime is governed by the high-end tails of joint distributions. Tl can explain why modelling flow is fraught with uncertainty. Yet since the flow is governed by the distribution tails, data are needed in this area. Since the required test data lie in the tail of the distribution, the probability of encountering the required data is very low. So either a very extensive testing program is needed to define the tails from field testing, or some assumptions are made and the tails are extrapolated from more easily obtained test results.

The models used to extrapolate the test data are based on the Fracture Network Approach developed by Jane Long[8] (the foundation of which was developed at MIT). Mr.

Doe recommends that the analyses should be based on field tests of flow measurements rather than on actual measurements of joint geometry. One intuitive advantage is that since we are attempting to model flow, this analytical basis reduces the number of analytical transformations of the data each of which could introduce modelling errors. This approach would also inherently account for the distribution of the joint aperture and extent. Also, there is the practical advantage that it would side step the nearly impossible task of obtaining the shape, aperture, and extent of the joints being modelled.

Mr. Doe proceeded to explain some of the pumping tests used to obtain data for an analysis and discussed the significance of the data. Pumping tests are the main vehicle for obtaining hydraulic test data. The tests can either be performed by injecting water at a constant pressure, and monitoring the flow rate, or they can be performed by injecting water at a constant flow rate and monitoring the pressure. He preferred using the constant head tests.

In the constant pressure injection test, the resolution of the data is governed by the flow meters. Using turbine flow meters one can measure roughly four to five orders of magnitude of transmissivity. For typical tests, the flow is limited on the high side by the water supply and by the pumps available at the site, typically 20-40 gpm. The lowest limit is governed by the smallest turbine flow meter, roughly 0.001 gpm, but can be further reduced by using a positive displacement type pump. The drawback with this sort of test is that accurate flow rates need to be measured at early times, and these measurements are difficult to make. As with constant flow rate tests, this test is also plagued with the problem of fracture jacking. As the pressure used in the test increases, the fracture may jack open. The jacking increases the flow rate (whereas in a constant flow rate test the recorded pressure drops). Once jacking occurs, the fracture can be assumed to have changed. Shear displacements can develop on the fracture, permanently dilating the fracture, and material can wash out of the jacked fracture, further increasing the flow rate. The permeability is almost always permanently increased. The advantage of this test compared with a constant flow test is that well storage effects become insignificant.

The fracture being pumped is considered as a confined aquifer. On initial pumping, the edges of the fracture are so far away from the advance of the water being pumped into the fracture that they do not influence the flow rate. But as the flow front starts to encounter restrictions in the fracture, the pressure across the restriction reduces the flow. If the "aquifer" is isolated, the flow will continue to drop. However, if it leaks into an intersecting fracture, a "leaky aquifer" is created and the flow will decrease at a lower rate. The curves of flow rate versus log time are used to determine the hydraulic aperture and extent of the fracture. ("Hydraulic" is used to imply that the quantities are not measured directly but rather are dimensions resulting from a hydraulic model. For instance it is assumed that the fracture is a round disk instead of being elliptical or rectangular, etc.) The transients after the reservoir depletion has been reached can be used to estimate the connectivity of the fracture system.

The problem with all down-hole pumping tests is that the important features may not be encountered. Flows may be strongly channelled. Instead of the flow being sheet-like, flowing uniformly through the fracture, the flow may be concentrated in the fracture, much like a river through the countryside. The chances of encountering such a stream

would be small. Thus, the parallel plate model may not be applicable. This flow characteristic also implies that the results of one, or a few, flow tests should not be used directly to predict the flow into an underground excavation, but rather should be used to develop a statistical flow model that could then be used to predict flows into an excavation.

From Mr. Doe's experience the fracture transmissivities follow a log normal distribution, or some other highly skewed distribution function. He estimated that 90 percent of the flow was channelled in 5 percent of the fractures. The mean of the transmissivity distributions decreased with depth, but the distribution extremes probably do not. At the Stripa site in Sweden, the distributions between 500 and 700 meters were all very similar. Mr. Gates indicated that the transmissivities at the Hanford nuclear waste repository site also followed a log normal distribution.

Finally, it is noteworthy that borehole pump testing is expensive. Mr. Doe found that it was not necessary to pack off individual fractures and test them individually. From a statistical point of view, a series of test sites using regularly varied packer spacings in which more than one fracture might be pumped at a time could also be used to develop the statistical distribution of the mass transmissivities.

John Osnes

Mr. Osnes presented highlights of the analytical developments that he has performed on statistical modelling of fracture flow in rock[9]. He had developed a three-parameter model and is using the data developed at Stripa (1700 tests, 25 km of borehole pumping tests at six sites, 20 percent of the holes of which had been tested twice with different packers spacings, each test lasting over two hours). He is currently improving his first model by developing better estimators. The model is based on the hypothesis of David Snow that since the total flow is the sum of the individual flows, the total transmissivity is equal to the sum of the fracture transmissivities. (This assumption implies that the fracture flows are independent.) A gamma distribution is used to model the transmissivities.

Although Mr. Osnes is trying to develop a good estimator for the mean and variance for transmissivity, he also states his concern that the distribution extremes play a significant role in water flow into underground excavations. He emphasized the characteristic of channelled flow through fractures that may not be correctly accounted for in his model.

On the subject of channelling, Mr. Meneley stated that the reaction between the water and the rock needs to be considered in estimating the extent of channelling. If the groundwater tends to dissolve the rock (gypsum, potash, etc.) channelling will develop. On the other hand if the water tends to precipitate out onto the fracture surface, sheet flow would tend to develop.

Day 2

Wendell Miller

Mr. Miller's presentation covered material developed during tunnel detection work. When water was pumped into boreholes, it flowed into an adjacent tunnel in well defined areas. He was not able to predict where along the joint the water would issue forth.

Instead of flowing through a fracture as a sheet, his experience supported the idea of channelling.

Other interesting results of his work were that there was no predictable communication between test boreholes and the communication was generally very limited. These findings were based on tracer tests. He also found a similar behavior to that described by Tom Doe with regard to the effect of fracture jacking on transmissivity. After jacking, the fracture transmissivity was permanently increased. The increase was variable and unpredictable. His tests also indicated that hydraulic compartments might also exist on a small scale. This also was established from the tracer tests.

Lynn Brown

Mr. Brown related his experience derived from the Bousted tunnel project located west of Leadville, California[10]. This tunnel was situated in two facies of granite. He established the need to treat the joints in each facies separately. When separated in this manner, distinct joint sets emerged in their stereographic projections, whereas when combined, the joint sets in the facies with the most recorded joints obscured the other joint sets. A direct result of this observation is that each facies should be treated as a unique hydraulic entity. The joints mapped at the surface were compared with the joints mapped in the tunnel. The conclusion from this comparison is that the act of tunnel excavation and poor blasting techniques increased the number of joints. This appeared in the mapping data as a decrease in joint spacing. The increased fracturing would tend to increase the flow rates into an excavation due to improved fracture connectivity.

Mr. Brown also presented a table[10] comparing predictions of flow into a number of tunnelling projects with the measured flows. The conclusion that could be drawn from this tabulation is that little confidence can be placed in predictions. Some of the predictions differ from the actual flow by several orders of magnitude. However, a few predictions were of the correct order of magnitude.

Rodney Smith

Mr. Smith presented information about the multipoint ("MP") pore pressure measuring system developed by Westbay Instruments Ltd[11]. The system can be used to measure fluid pressure distribution in a borehole. The resulting pressure measurements can be used to establish the natural groundwater flow regime or monitor the response of the groundwater system to pumping tests or an underground excavation. In addition, any type of response test (for example variable head, constant head, constant flow, or shut-in test) can be performed in any or all of the isolated sections in the drill hole. Water samples may also be collected from each of the isolated test sections. A test section is established by installation of a port into the casing wall. Each ported section is isolated by backfilled material or casing packers. More than 30 sections have been installed in a single drill hole. The cost of the installed instrumentation is roughly equal to the cost of drilling one instrumentation hole.

He presented case histories in which the instrument was used. At Hanford, 15 test sections were installed in a single 4,000-ft drill hole. The equipment was also used at Downie Slide and Dutchman's Ridge Slide on the Columbia River. At these sites, the

increased data density helped to identify hydraulic features which were not identified by drill core logging and would be missed by less dense permanently installed standpipe systems or transient, open-hole packer tests. Mr. Smith concluded from his experience with the MP system that the hydrogeologic regime of natural rock systems can only be understood with a high density of data points permanently installed. Only in this way can the response of individual fractures to natural and induced perturbations be correctly identified. Although modelling is an important tool in evaluating inflows and fluid pressure response, the accuracy of the model will only approach the accuracy of the input data.

William Meneley

Mr. Meneley's experience is based in the potash mines of Canada. It is due to this experience that he made the comment that flows which dissolve rock create karst-like flow paths and channelled flow, whereas flows that precipitate material in the fractures will tend to create more uniform flow regimes. For potash these mechanisms are important because it can be so quickly dissolved. For other rock types the time scale for movement on fractures and fracture creation may overshadow the time scale of deposition and dissolution activity.

In Saskatchewan, there are nine conventional shaft potash mines and one solution mine. Major water inflows (> 1,000 gpm) have been encountered at three of these mines. At one mine the inflow was successfully stopped. At another, efforts are still continuing to stop the inflow. The third mine has been flooded and converted to a solution mine. Flooding poses a significant threat to conventional potash mines in Saskatchewan.

Down to a depth of about 3,000 ft, conventional mining techniques have been used to exploit potash reserves. Deeper than that, solution mining techniques are used since the high creep rate of the potash closes the excavation too quickly. Water inflow problems occur due to the presence of regionally extensive aquifers overlying the potash deposits. These aquifers form part of a regional groundwater flow system which extends eastward from the Rocky Mountains in Alberta and the northern United States to the Precambrian Shield in Manitoba. This aquifer is recharged by local precipitation downward through the overlying confining strata. Due to the continuity of the aquifer system, the hydraulic head in the aquifer is reliably predictable. Because the storativity is very low, a significant leak from the aquifer into a mine can be identified in observation wells 0.5-5 miles from the leak within 5-50 minutes following the onset of leakage.

The location of an inflow into inaccessible mine workings can be determined from the pressure response in properly completed and instrumented observation wells. Microseismic monitoring has also been used successfully to delineate the location of leakage into potash mines. After an inflow occurs, plugging the leakage has been done by constructing bulkheads to seal off the leak within the mine, or by extensive grouting operations. In addition to grouting, pressure relief may be required to reduce the hydrostatic pressure by means of controlled inflow into boreholes drilled into the aquifer from the mine workings.

To gain access to the underlying potash, shaft must be driven through the overlying aquifers. Freezing techniques have been used successfully in shaft sinking operations to

prevent water inflows and to support the excavation prior to placement of the permanent concrete or concrete/steel shaft lining.

Jane Long

Mrs. Long's presentation addressed the numerical modelling of groundwater flow and reviewed some of the related work being performed at Lawrence Berkeley Laboratory (LBL)[8,12,13].

She also thought that flow might be channelized within the fractures. Thus, the parallel plate model may not be sufficient for modelling flow through jointed media unless the fractures are open. If the fractures are very tight, then flow channels develop. But for the case of partially closed fractures, the flow model is undetermined.

She has performed parametric studies on a fracture network assuming a Poisson distribution for the fractures. The fractures were modelled as lines with varying lengths, various spacings, and centers. The connectivity of the model decreased drastically as the length of the fractures decreased, and as the fracture length increased, the model started to behave as a homogeneous medium. As the aperture distribution became broader (keeping the mean aperture the same), the mass conductivity decreased. If the fractures with large radii were assigned the larger apertures, but keeping the same probability distribution, the mass conductivity increased. This is not surprising in light of the minor role that the small fractures play in determining the total mass conductivity. When comparing the conductivity of the 3-D models with that of the 2-D models, the 3-D models always yielded abnormally high conductivities. The 3-D model is considered to be over-connected while the 2-D model is considered under-connected. From these studies, Jane Long has concluded that since 80 percent of the fractures do not play an important role in the flow regime, the fine detail of the region need not be modelled. The question still remains however, how one determines which detail to neglect.

Moving on to the importance of shear zones on the hydraulic regime, she stated that shear zones dominate the hydraulic behavior of a rock mass. She believes that it might be possible to develop a fracture mechanics approach to develop a realistic fracture pattern. The tension cracks and anastomosing shear cracks lead to an interconnected fracture network that could be used as a basis for analytical flow models.

In addition to this approach, Mrs. Long is developing and studying a channelized flow model. This model will be able to establish the role that flow channels play in determining the conductivity of the rock mass.

Lawrence Berkeley Laboratory is also investigating water flow near shear zones. It appears that most of the flow was found in the shear zones, even though many individual fractures were found to be infilled. In another project at the Stripa mine (Sweden), seismic and radar tomography tests and crosshole well-pumping tests will be performed to obtain data for hydraulically modelling the shear zones.

Ian Farmer

Dr. Farmer summarized case histories of longwall coal mining beneath the sea and beneath the Permian aquifer in Northern England[14]. Under normal circumstances, the presence of low permeability mudstones and underclays (seat earths) in the Coal Measures cyclothem prevented flow of water into the mine workings. When the disturbed zone above the workings - related to the width of the excavations - intersected the seabed or the aquifer, significant inflows were observed. These were associated with an estimated 0.6 percent strain induced at the base of the water source by excavation. Other factors shown to influence inflow were the cover depth and the proportion of low permeability rocks in the succession.

Daniel Hokens and David Becker

Mr. Becker presented an analytical method that he used to investigate the feasibility of a Deep Base from the stand point of water inflow. He developed the analysis based on a continuum model, using Bear's well equations[15] for the shaft, and Goodman's equation[1] for the tunnels. To account for rock layers of differing transmissivities, he used an average, weighted by the layer thicknesses. Then the flows were evaluated for each segment of the rock mass, and then as the tunnel advanced, the flows were summed as new segments were added to the excavation.

Jesse Yow

Mr. Yow presented his experiences associated with the excavations in Quartz Monzonite at NTS in the Climax Stock[16]. This rock mass contained eight joint sets. The fractures accounted for only about 2 percnet of the rock mass porosity. Although the tunnel (at 1,400 ft) was above the regional water table (1,800-2,000 ft), a number of seeps occurred along the major fractures. The flows were affected by the fracture extent and orientations, the drift orientations, and the stresses in the vicinity of the excavations. Although not a problem with regard to flow rates, the seeps ruined a number of instruments in the tunnels.

Mr. Yow also described the behavior of the water in the welded tuffs at NTS in Yucca Mountain. He reported that the welded horizontally bedded tuffs are moderately to densely fractured, with the fractures oriented subvertically. The matrix porosity of the tuff ranges from 10 to 20 percent, and the rock is thought to have a saturation of about 60 to 80 percent. The excavations are well above the regional water table, but problems may be encountered due to perched water.

He described the work the Lawrence Livermore National Laboratories (LLNL) were doing on the Canadian Underground Research Laboratory (Lac du Bonnet, Manitoba) water flow modelling study in which the effects of tunnel excavation on water inflow were modelled. The predictions were not complete, and LLNL is working on a fully coupled code in which flow, stress, and temperature are accounted for. A solution for fracture deformation and hydraulic flow rate has been developed for coupling hydraulic and mechanical responses during fracture jacking or deflection and will be incorporated into the code[17].

Christopher St. John

Dr. St. John presented the work of one of his colleagues, Margaret Asgian[4,5]. Ms. Asgian developed a 2-D stress-deformation coupled flow model in an effort to understand anomalies that developed in some pump injection tests. The results of the computations show that flow occurs primarily along discontinuities that undergo shear deformation. It should be noted that the work that Tom Doe did substantiates this response. William Meneley has also experienced this behavior as well as the anomalous low pressures that were predicted by the analysis at some distance from the injection point. The model highlighted the fast response of the rock stress to initial injection pressures, and the slow response of water pressure, requiring the flow of fluid to develop a response.

The analysis could be used to detect tunnels, estimate the early time flows into excavations, and transient flows such as might be expected when loaded by a nuclear blast (although more work would need to be done on this last option). It might also be possible to investigate the influence of tunneling techniques on the flow rates of water into an excavation. Drill and blast techniques could be compared to a bored tunnel.

Peter Lukins

Mr. Lukins spoke about the contractor's perspective of ground water problems. One problem is a matter of safety. Sudden large inflows have been known to kill workers. However, this is not a common occurrence. The water can also soften the rock enhancing deformation and reducing stability. Another problem is that water tends to slow productivity. In one case, water slowed the rate of advance from 140 ft/day to 70-80 ft/day. Water can reduce visibility, make the ground slippery, and generally complicate work conditions. Water can impair the power of a TBM's gripping pads, and it may dictate use of a less efficient means of mucking.

Practically speaking, water is handled by gravity or pumping. He recommends planning for eight times the amount of water estimated by the engineer. What may start as a water nuisance may end up as a major problem. It may seem that small seeps need not be handled. In the long run, they will accumulate on the floor forming a slurry that could damage the rail for the mucking cars. Water trapped behind the concrete forms can also damage the cast concrete. From the perspective of water management, the tunnel should be inclined slightly upward (up to the point that rail can no longer be used). Downward inclines are decidedly bad as the water collects at the face, which is the center of activity. Grouting to reduce water inflows is not a preferred technique for the tunnelling engineer because it interferes with excavation activities at the face, effectively delaying the advance.

Kendzi Karasaki

Mr. Karasaki presented some of his work on modelling flow in well tests in fractured rock[12,13]. He assumes a homogeneous flow at distance from the borehole and near the bore he resorts to 1-D linear flow, more accurately modelling the fracture flows where the flows are more concentrated.

3 Review of Submitted Papers

The following articles were brought to our attention by participants at the conference, as germane to the subject of ground water in a deep base. Several were discussed at the workshop.

Experiences Gleaned from Case Histories

West Dreifontein Flood[2]

This huge flood occurred in one of the largest African gold mines. The mine was situated below the water table in dolomites that contained large solution cavities. During mining at a shallow depth, the rock started "talking" and by the end of the shift, large amounts of water were pouring into the mine. The inflow rates were on the order of 67,000 gallons per minute (gpm). The mine was saved after a few weeks of heroic efforts to plug the tunnels which connected the water source to the remainder of the mine. The mine was almost lost, but saved due to the cooperative efforts of the neighboring mines and the power companies. The maximum pumping rate was on the order of 60,000 gpm and consumed 137 megawatts of power. The installed seals had to withstand a 4,000-ft head. To continue mining the flooded portion, a decision was made to dewater the dolomite compartment. It was estimated that 1-1/2 hours were required to dewater the unit.

West Dreifontein Mine[3]

The mine was excavated using the Francois Cementation Process (developed in 1916). This process consisted of drilling a fan of holes forming a cone around the location of the future tunnel. The holes were then grouted with cement grouts. If there were fine fissures, waterglass was injected, followed by injections of cement grout. This technique successfully sealed off flows of 10,000 gpm.

The rate of water inflow was found to be influenced by the extent of ore extraction. At depth, the supports were not sufficient to keep the excavations open. Thus, after mining, the excavations were permitted to collapse. The consequent settling caused the rock to fracture, opening more flow paths, increasing the flow into the excavations.

Efforts were made to seal the mine workings from above. Over the excavations, umbrellas of interconnected holes were drilled and injected with grout. The grout umbrella reduced the flows into the mine, but once settlements occurred, the umbrella was breached and the water flow rates increased.

Tunnel construction was historically very difficult in this region. It took three years and $5.5 million to sink the #3 shaft to 4500 ft. These shafts were driven under "cementation cover." A 450 ft long probe hole was always drilled in front of the face, looking for water. In addition, no less than four probe holes were drilled in the face which extended at least 4 ft past the blast hole depth. All fissures encountered in these probe holes were injected with grout to seal off water flows. Sometimes these probe holes would encounter high flows. In at least one case, a 1-2 in. diameter hole produced roughly 10,000 gpm.

When the flood occurred, the water came from a fault plane that had opened in response to mining. A previously tight fault was opened by a quarter inch. This fissure connected the workings to the regional water table. The flow rate did not decline as it had in other occurrences of a breached water source. The more common experience was for the flow rate to reduce as the source became depleted. In this situation, the source was so large compared with the volume of the mine that it could be considered infinite.

Summary of the Dreifontein Experience

The experiences gleaned from the Dreifontein Mine indicate that caution should be taken when addressing water inflow. The mine is situated in a rock formation that contains large water filled voids and thus the water flows are not predictable, and potentially very serious. For a Deep Base, this lack of predictability and the response of water flow to mass fracture would screen out potential Deep Base sites containing such rock types.

The Dreifontein experience also provided some experience in water sealing measures. The grout umbrella provided some relief from water inflow, but was fragile and may be susceptible to damage from blast loading and from rock movement. Perhaps flexible grouts could be substituted for the cement grouts. The experience also provides some insight into a means of repairing damaged excavations resulting in water inflows. The mishap also emphasized the large amounts of power required to dewater a flooded excavation, and the great expense of sealing a tunnel under construction in wet ground.

An Introduction to Physical Geologic Factors Affecting Groundwater Inflow into Large Bore Tunnels[6]

Dr. Roger's paper lends insight into the factors and conditions that influence groundwater flow into underground excavations. The dominating influence of fracture flow is emphasized over flow through the rock pores. He further expounds on the occurrence of regular joint sets and the mechanisms by which they are created. These hypotheses are supported by examples of field observations. Some graphical correlations between the rock structure and fracture spacing are presented. He suggested examples of geological settings that might pose water inflow problems. In his presentation, Dr. Rogers also discussed a number of case histories in which insufficient attention had been paid to factors contributing to serious water inflow problems.

The paper and presentation do not address modelling of water flow directly, but provide a background highlighting factors that need to be accounted for in the exploration and analysis of potential flows into an underground excavation. The presentation stresses the importance of fracture flow and the important variations in flow due to rock mass structure. It also stresses the unique nature of each excavation. These considerations lead to

the conclusion that generalized analytical approaches may have limited application. Each potential site and excavation needs to be evaluated in light of its own unique geologic setting, rock mass structure, sources of water, geometries, etc.

Hydrologic Response to Nuclear Detonations[18]

The paper reviews observations of water response to nuclear blasts. The paper points out the limited nature of the observations and highlights the quandary of the analytical community. A major question stands; how to analyze water flow. The inclusion of dynamic loading adds many more variables that need to be assessed. Does the water flow in direct response to the high blast stresses, or are the induced stresses more important? Tectonic activity following long after an event indicates the blast effects may be long lasting.

The report highlights three subjects that need to be addressed: how water responds to changes in stress in the rock mass (how these stresses move water in the vicinity of those stresses.), how distant are the influences of these stresses (These two questions could probably be addressed using static conventional flow analyses and fracture flow analyses.), and how do blast flow stresses change the rock mass conductivity. Block motions could either open flow paths, or as suggested in one event, consolidate filled joints, reducing their conductivity. Blast effects could also fracture the rock mass (either in the sense of microhydrofracturing, or in the sense of creating large new fractures), increasing the overall permeability. These effects would influence the water flow even though the induced stresses subside.

Mr. Rawson also points out another important water-related event; the stimulation of block movements due to tectonic stresses as modified by blast-induced water pressures. Long after a blast, the water pressure in collusion with the tectonic stresses could cause a block motion, which might disrupt the Deep Base.

Data Summary Presented by Lynn Brown[10]

Lynn Brown presented two tables of data pertaining to water flow and its prediction. From this set of data, two important conclusions are drawn. First, extrapolation of joint spacings found at the ground surface down to tunnel levels might be misleading. In examples cited, joint orientations as well as joint spacings at the surface differed from those measured in the excavation.

Second, we have not been universally successful in predicting groundwater flows. In Mr. Brown's table, estimates often differed from the measured flows by one order of magnitude (eg. 5,000 gpm estimated versus 200 gpm actual, or 200 gpm estimated versus 30 gpm actual) and the estimates offered by different people varied substantially.

The data indicate a need to either understand the problem better, or come ot the realization that such natural phenomena are not amenable to deterministic analyses, and probabilistic analyses might be more suitable.

Groundwater Control in Tunneling, Volume 1: Groundwater Control Systems for Urban Tunneling[19]

The report consists of three volumes, dealing with control of groundwater in underground and open excavations. The first volume does not deal with the analysis or prediction of water inflow. It is a synopsis of common practices used in dealing with water in civil structures, typically at relatively shallow depths. The focus of this volume is on the control of groundwater during tunnel excavation. Of particular interest, relating to a Deep Base site, are their comments on the site investigation techniques and planning starting on page 18. These are recommendations for a conventional civil structure and need to be more rigorous and detailed for a military structure that must remain intact and functional during and after an attack. Due to the great depth of a Deep Base, the increased rigor implies a correspondingly larger cost for the design phase investigations (preliminary investigations may not be so extraordinarily more expensive, but that depends on the site under investigation. In the case of NTS, the site is so well characterized that preliminary investigations may not even be required. However, in poorly investigated areas, the preliminary investigations would also be very expensive.)

Another relevant portion of the volume is their coverage of conventional grouts, their advantages, characteristics, and relative costs (starting on page 77). Since grouting is one of the leading candidate methods of sealing water tunnels (whether as a primary sealing mechanism, as a backup system or for repair measures), this review provides a particularly relevant base for directing future research in choosing the most appropriate grout for the Deep Base application.

Other methods for curtailing water inflows are presented, but these are mostly relevant to soil tunnels.

Groundwater Control in Tunneling, Volume 2: Preventing Groundwater Intrusion Into Completed Transportation Tunnels[20]

The second volume in this series deals with measures to prevent or reduce water flows into completed excavations. As with the first volume, this volume does not deal with the prediction of groundwater flow into tunnels. However, a number of topics addressed have indirect interest to the Deep Basing community. On page 5, it is acknowledged that ground movements associated with pile driving will tend to crack a tunnel lining, creating new paths for water flow, and augmenting existing flow paths. Perhaps such a case history could provide a basis for evaluating the resistance of a lining system to dynamic loading.

On page 14, R. B. Peck is quoted as saying that to completely waterproof a tunnel at 2,500-ft depth in rock of fair to good quality, a tunnel with a 20-ft diameter would require a 32-1/2-in. concrete lining. This quote seems to be based on the need to support the full hydrostatic pressure. The implications of this general comment need to be assessed for each geologic setting. Perched tables, aquicludes, and groundwater flow regimes would tend to reduce the water pressure felt by the tunnel.

With regard to possible liner designs, Ferro-Cement (page 36) which is used in boat construction, might be an interesting and novel method to design a Deep Base lining to be

able to withstand the high loads, and, although cracked, may be able to maintain its integrity and continue to support a water-sealing member situated outside the ferro-cement structural lining.

Starting on page 38, various waterproofing envelopes are discussed. These impervious liners are used to waterproof tunnels in which water can not be tolerated. Some of them seem promising for use in a Deep Base. One in particular, butyl rubber sheeting (page 49) has the decided advantage that it cold flows, sealing small holes. In addition, it stays flexible with the passage of time. Other water sealing systems are also discussed, including bitumen impregnated layered systems that resist lining tearing and bitumen flow, synthetic sheeting, and sprayed on fluids used to seal the concrete structural lining.

The volume also has a section on grouting that more or less duplicates the coverage in the first volume, but with a few added details.

Groundwater Control in Tunneling, Volume 3: Recommended Practice[21]

This volume summarizes the first two volumes and adds a few examples of water prevention measures to demonstrate the application of the principles presented in the reports.

The three volumes provide good background on dealing with water inflows into excavations. Unfortunately, the bulk of the work deals with shallow tunnels and with methods of preventing the water inflow, rather than with deep tunnels and methods of estimating the water inflow. Thus the report is unfortunately not entirely relevant to the objective of this symposium.

Analytical Techniques

Application of Idealized Analytical Techniques for Prediction of Mine Water Inflow[22]

This paper summarizes various analytical methods for estimating water flow into an underground excavation. The approaches analyze very simplified configurations in homogeneous materials and therefore are not suited for predicting flows issuing from discrete fractures. However, the analyses might be used to estimate the average flow into a large tunnel complex, given statistically significant input data. Alternatively, as suggested in the paper, numerical analyses could be performed to account for deviations from the geometry on which these analytical forms are based. Analyses as discussed in this paper provide a starting point for computing flow into a Deep Base. However, predictions need to account for aquitards, perched water tables, and fracture flow, all of which would greatly influence flow.

Groundwater Inflow Analysis at Deep Basing Site (Generic Mountain C) for Horizontal Deployment Tunnel in Formation 8 and Vertical Muck Shaft in Formation 9[23,24]

Two reports were submitted by Richard Gates, both dealing with the analysis of water inflow into excavations constructed in Generic Mountain "C". The first calculates the projected water inflows using existing analytical solutions. The second (Implication of Generic Mountain C Groundwater Conditions for Reference Concept Egress) uses a

numerical code developed by Golder and Associates. The report authors noted that, although the results are conservative, water inflows due to secondary permeability (flow through fissures, joints, etc.) would be expected to be 2 to 5 times the flows calculated.

In the instance of this report, it would seem that the shortcoming of the analysis lies in the set of data that describes the site imperfectly. A great deal more effort must be made in obtaining hydrologic test data if a site is to be characterized and modelled with confidence. With such sparse data, sophisticated analyses can not be launched. With a statistically significant data population, more realistic and complex models can be exercised, parametric studies can be performed, and probabilistic approaches could be developed.

A Numerical Model of Fluid Flow in Deformable Naturally Fractured Reservoirs[4]

This paper summarizes Ms. Asgian's PhD thesis (1987 University of Minnesota) in which she modelled fluid flow in an infinitely extending 2-D mass subdivided by joint sets, and subjected to stress of fluid pressure (using the program FFFLOW that she developed). It is a fully coupled analysis. The stresses and deformations of the rock are determined using a boundary element method and the fluid flow is calculated using a finite difference routine. The flows are calculated explicitly, whereas fluid pressures are calculated implicitly and simultaneously with the rock deformations.

The analysis will probably prove to be useful. However, it needs to incorporate a few minor improvements. The element on which the analysis is based is 1 unit thick. A portion of this unit is closed and another portion is open, allowing passage of fluid along the joint. As the joint opens, it is assumed that the aperture opens, and naturally more fluid can pass through. However, it is not clear from the presentation whether or not the contact area of the joint changes. The contact area (1-n) should decrease as the joint opens. There are only 4m unknowns (stresses and strains of the blocks and flows and pressures of the fluid times m joints). The analysis disregards rotations; blocks are only permitted to translate. This may not be particularly important when the area of interest is fully constrained by other blocks. However, near an excavation boundary, block rotations are probable and can open large flow paths.

A few examples of the code's use are presented. The analyses are used to explain the behavior of reservoir injection tests. Although the report does not compare the analyses directly with field test data, the computer results predicted limited areas of reduced pressure that have also been experienced in the field (however not for the same geometry).

This work is certainly a great improvement over the continuum analyses of homogeneous materials that have been prevalent for a long time.

Characterization of Fracture Networks for Fluid Flow Analysis[8]

This paper presents a comprehensive overview of new network flow modelling techniques that are being developed at LBL. The approach is comprehensive in that it draws upon computer modelling techniques incorporating statistical methods, pumping test data, laboratory test data, and geophysical techniques to develop the flow network. The paper begins by presenting obstacles in the path of accurately modelling flows in a fractured

media. Such characteristics as unknown joint apertures, uncertain significance of pump tests, the significance of extrapolation of outcrop data to larger scale 3-D characteristics, and unknown joint orientations, extents, shapes, and connectivities are some of the sited stumbling blocks in the way of correct network models.

The paper proceeds to address how inroads can be made into some of these areas of uncertainty. A method is described of how on the small scale (on the scale of inches to feet) to gain an appreciation of the fracture aperture by use of RTV rubber fracture injection casting. This technique could lead to a better understanding of the intermediate flow regimes (i.e. between sheet flow and channelled flow). Then combining geophysical techniques, pumping tests, and statistical regression analyses, a method to characterize fault zones is presented. This approach seems a bit convoluted but it does lay out a framework from which the flows in a shear zone could be predicted (better than we would otherwise have). Where uncertainties exist in the approaches, statistical techniques are implemented to express the appropriate uncertainties involved. Cross hole geophysical tests are used to locate the shear zone and used as a basis to develop a probability of encountering a conducting zone as a function of location through a section of the zone. Once the model is developed, it is adjusted to match the results of borehole tests.

The techniques presented in this paper are very much in keeping with the comments made during the conference, that a great deal of testing is required to properly characterize a hydrologic unit. The paper presents a well thought out methodology for analyzing flow through a fractured rock mass. However, with regard to a deep underground excavation, the required testing may be prohibitively expensive. Perhaps a criterion should be developed for establishing the important zones that need to be characterized (i.e. the shear zones), thus concentrating the financial resources where they would do the most good. Putting the problem in proper perspective, it will never be possible to fully characterize a site and to know where that big disastrous inflow will occur, but using techniques such as those presented in this paper, it should be possible to examine "what if" scenarios (i.e. what are the statistics of blast altered flow?).

A New Analytic Model for Fracture-Dominated Reservoirs[12]

Mr. Karasaki has developed an analytical model for interpreting the results of well injection tests. The model consists of three concentric zones. The flow in the outermost zone is radial, through a homogeneous material. Flow in the innermost zone is linear, which is to say through radial fractures that connect the outermost zone to the well. Then the third zone is a very thin, infinitely conducting zone between the inner and outer flow regions. The purpose of this zone is to couple the two zones of interest. The analysis is a 2-D formulation, modelling fractures that run parallel to a borehole. Much of the paper deals with the behavior of the equations, and an appendix presents a summary of equation derivations.

The scheme suggested by Mr. Karasaki has potential applications in computer analyses of flow regimes. In modelling large flow networks, an inordinate number of calculations and computer storage would be required to model the whole network of fracture flows individually. However, moving farther away from the point of interest (the deep excavation), the quantity of flow in an individual fracture becomes less significant than the same quantity of flow closer to the point of interest. Thus, it may be possible to model the

fractured rock far from the point of interest as a homogeneous equivalent material. Then, following Mr. Karasaki's example, an envelope of infinite conductivity could divide the homogeneous region from the discretely fractured region, distributing the water into the discrete fractures.

Analytical Models of Slug Tests[13]

Karasaki et al., summarize a few 2-D analytical solutions to flow that can be used to interpret the results of slug tests. Two spherical flow solutions are also presented. Two solutions contain mixed flow. The 2-D mixed flow scheme consists of linear near the bore, and radial flow beyond the linear region (see the previous paper by Karasaki). One of the 3-D flow analyses incorporates an inner radial flow zone and a more distant spherical flow zone.

The paper presents the governing differential equations, the boundary conditions, and the plotted solutions in a dimensionless form. The solutions generally require the use of Laplace transformations and a numerical inversion. Thus, the application of these techniques are not amenable to closed form solution.

Each of the solutions is based on different boundary conditions and flow regimes, thus suitable to a different fracture geometry. It points out the difficulty of interpreting the test results. Several analyses can be performed and the test results compared with the analyses. It could be concluded that the field geometry corresponds to the analysis that is matched most accurately. The unfortunate drawback to this reasoning is that, for the logic to hold, not only does the analytical model have to model what it purports to model correctly, but one has to be able to model many geometric boundary conditions and flow regimes, possibly a very extensive task.

Groundwater Inflows During Tunnel Driving[1]

The first section of this paper presented a background for understanding the sources of water in underground excavations, the locations where groundwater might be encountered, and the trouble that the flows create. Then, the body of the paper proceeded to analyze three specialized cases of water inflow. A different analytical technique was used in each case.

In the first case, of the 2-D flow entering a buried pipe, a complex analysis is used in the method of sources and sinks, assuming a homogeneous and isotropic material to calculate the steady state flow into a tunnel through its walls. This is the solution that can be approximated by drawing a flow net.

The second case analyzes a square tunnel on the verge of entering a water bearing pervious zone from an impervious zone. The transient flows into the face are analyzed using a finite difference scheme developed by Paul Witherspoon (University of California, Berkeley). To make these results more applicable, the solutions were graphed in parametric form. These solutions assume a homogeneous isotropic material.

The third analysis was based solely on model studies, and deals with the transient flow of water through the face or walls of a tunnel as it passes through a water bearing

pervious zone. From these tests an empirical flow equation was developed for inflows with a declining water table. This analysis also assumes a homogeneous, isotropic pervious medium (in as much as sand is hydraulically isotropic). These approaches may be inappropriate for the case of a rock mass with fracture spacings on the order of the tunnel diameter or greater.

This paper highlights many of the analytical problems that need to be addressed. As pervious zones are penetrated, large inflows that decrease quickly with time are shown to be expected and are in fact found in the field. However, the assumption of homogeneity is too simplified for many cases. This paper made a start on a problem that can now be advanced via the powerful computational tools at our disposal. Now it should be possible to analytically model more realistic boundary conditions, embracing discrete fracture flows, and cast the data and results in a non-deterministic form.

Probabilistic Approach to Predicting Groundwater Flow into Deep Tunnels[9]

John Osnes presents a concise development of a probabilistic method for interpreting borehole pump test data. He further illustrates the use of his analysis with a simple analytical flow model, showing how the transmissivity statistics derived from the test data are used to calculate the probability of the flows exceeding a given rate.

His transmissivity probability density function uses four parameters that need to be estimated from the pump test data; the mean frequency of fractures, the probability of encountering a conductive fracture, and the scale and shape parameters of the gamma distribution that characterize the transmissivities of a conductive fracture. The resulting probability density function is verified using a large data set developed in the Stripa project in Sweden and seems to appear adequate.

The last section of the report applies the principles that are developed to predict the probability of encountering flow into an excavation under a body of water. The model used to cacleulate the flow into the excavation is that proposed by Goodman (1965)[1]. This example is a clear portrayal of the difference between the derivation of model parameters and the analysis of flow into an excavation. It is made clear from this report that there are two distinct aspects to the groundwater flow modelling problem. One question is how does one model flow, and the other is how does one obtain the parameters for the model? Osnes' work concentrates on obtaining the model parameters.

Before blindly applying this analysis to borehole test data, it would be wise to understand the basic assumptions underlying the probabilistic developments. If these assumptions are generally not valid, the analysis would have to be reworked to account for the variations. Thus, in closely jointed rock, the basic assumption of isolated conducting paths is not valid. In this case, it might be more appropriate to assume the mass is a homogeneous conducting material and alter the statistics accordingly. In addition, the flow regime on which the analysis is based needs to be understood. If the flow is not radial Darcian flow, for example if channelling occurs, the analysis would have to be altered.

A Similarity Solution for Coupled Deformation and Fluid Flow in Discrete Fractures[17]

This paper analyzes one dimensional flow of water through a planar fissure, as a function of the stress on the fracture. It is a coupled problem in which the joint deformations influence the joint apperture and therefore the transmissivity of the fracture, and the fluid pressures in turn influence the effective stress on the joint. The analysis is started by making simplifying assumptions to ease developing the closed form analysis. Once the closed form governing equation have been derived, the system of equations are solved numerically. The results of a sample problem are presented to demonstrate the use of the analysis for test planning purposes and for analysis of test data to derive fracture properties. The analysis was also intended to be used to test complex computer codes.

Instrumentation

Multiple Level Groundwater Monitoring with the MP System[11]

This paper reviews a groundwater monitoring system manufactured by Westbay Instruments, including its construction, installation, and operation. The advantages of this instrument is that it requires only one probe to monitor multiple level monitoring points in a drill hole. The equipment is quickly and easily installed and there are a number of equipment cross-checks to verify and thereby improve the quality of the data. The current probe is designed to operate to depths of 5,000 ft on a standard single conductor wireline. Several installations are currently in successful use at depths of 4,000 ft. Westbay (personal communication between Smith and Patton, 1989) anticipates that installation to greater depths does not pose a significant technical problem. A current disadvantage is that monitoring is performed manually by moving the probe from port to port inside the casing. However, Westbay (personal communication between Smith and Patton, 1989) currently has a prototype system which allows simultaneous remote monitoring of more than 30 probes in a single hole.

Evaluation of Hydraulic Properties of Rock Masses[25]

The recommendations and suggestions made in this paper are founded on practical construction experience. The paper highlights the importance that water barriers play in causing water related problems during construction of underground excavations. The authors view problematic rock masses as fairly homogeneous volumes of hydraulically similar rock separated by thin seams of relatively impermeable material. Major problems can occur when an excavation approaches an impermeable seam. In response to a high head on the far side of a water barrier, the face can blow in, causing instantaneous flooding.

The authors suggest using conventional aquifer evaluation techniques (which are based on assumptions of homogeneity) to evaluate the more permeable rock, and present two methods for locating thin water barriers, one using piezometers, and the other using probe holes in front of the excavation face and performing specialized packer pumping tests.

These recommendations are applicable when addressing the construction of underground excavations in rock masses that can be approximated by hdyraulically homogeneous media. However, for a rock mass containing few hydraulic conductors, the approach may not be well suited. Even though the experience does not address long term flow rates, it does point out a danger of a water retaining impermeable seam. It could flood a Deep Base if the seam were breached as a result of blast loading.

Review of Contributions to the International Congress on Tunnels and Water

The Proceedings of this congress addressed many of the topics broached during the WES waterflow conference. The themes covered in the Madrid conference embrace accounting for water in design of tunnels and underground works, the effects of water in construction of underground works, underwater tunneling, and special aspects of hydraulic tunnels. Although many papers were presented in this two volume Proceedings, only a selected number were thought suitable to highlight and note here. The following is a listing with a brief comment of some of the more relevant papers, all from Volume 1.

A. Haack - on sealing tunnels in Germany, p. 155.

L. Jinhuo and S. Guangzhong (two contiguous papers beginning on p. 193) giving an empirical approach to predicting tunnel inflows. This is a very basic and simple decision tree analysis of geological factors bearing on water inflow. It may be usable by military planners.

R. Casale, C. Comin and C. Focacci - on scaling up flow predictions from pilot bores for estimating flows into larger excavations, p. 63.

M. Junzheng - on application of fuzzy set theory to predict water inflows, p. 211. This touches on an interesting area but is difficult to understand.

J. Reith - on impermeabilization of underground works (in French), p. 283. Reviews concepts, including drainage, construction of an "umbrella" arch, philosophy and materials for grouting, details, and other aspects.

J. Rivas - on impermeabilization of tunnels (in Spanish), p. 291.

C. Scheu - protection and drainage of tunnels using geotextiles (in Spanish), p. 313.

Jorg Schreyer - sealing shotcreted tunnels, using resins and special construction procedures where there is no final lining, p. 317.

V. Astad and P. Heimli - waterproof shotcrete for tunnels, p. 393. This important paper discusses a new development from Norway. Shotcrete can be made to be essentially impermeable by constructing it to have low porosity, high strength, and good bonding with the rock. This is achieved by the following details: 1) using an aggregate gradation from 0 - 12 mm (following ACI code 506.2); 2) using a low water cement ratio (less than 0.5) with water-reducing admixtures to yield workable slump in the range of 15 - 20 cm; 3) use of microsilica filler of grain size 0.1 to 0.2 microns as 5 - 10 percent of the weight of cement; 4) use of steel fibers (1 - 2 percent by volume) to resist crack opening; 5) use of

low accelerator content (3 - 5 percent); and 6) use of curing compound and wetting of the shotcrete surface for the first week.

W. Cornely - on polyurethane grout for stopping water, p. 413.

J. Gran - on watertightness of linings for tunnels of the Prague subway, p. 455. This paper considers the chemical aggressiveness of groundwater on rock and lining and measures to prevent corrosion of the lining.

Y. Kiritani - on watertight, extruded, reinforced concrete linings, p. 481.

N. Navalon and J. M. Lopez Marinas - on groundwater flow prediction and control for an underground complex in limestone (in Spanish), p. 557. This paper discusses a scheme for prediction using the geohydrology of the rock mass.

T. Saotome - on handling water inflows using the New Austrian Tunnelling Method, p. 597.

4 Further Discussion and General Comments

Analyses of groundwater flow into underground excavations have relied heavily on the analyses developed for well pumping tests. In addition, numerical techniques have also been added to our analytical battery. Most of these analyses assume a homogeneous medium or a combination of various homogeneous media. In fact the medium through which the water flows is typically discontinuous, and the water flows along discrete channels.

The tacit assumption is made that the continuum analysis approximates the real situation. Little effort is given to prove that this approximation is appropriate. Certainly, if the joint spacing is large compared with the excavation dimension, the approximation will be inaccurate. However, if the excavation is large compared with the joint spacing, then the assumption may be more reasonable if total flows are being calculated. However, flows from short sections of the tunnel will probably not be very predictable.

Another tacit assumption that is often made is that the data on which the analysis is based characterizes the site properly. This is probably the weak link in the analysis of water flow into underground excavations. An instance of this is the data used to describe Generic Mountain "C", described in the report by Shannon and Wilson. There are very few "boreholes" from which the data were derived. In addition, since the boreholes are so small compared with the joint spacing, they are not representative of the hydrologic regime of such a large area. More holes would be required to develop a statistically significant data base from which to derive average parameters for an analysis (to estimate average total flows) or to provide statistical distributions for a probabilistic analysis.

The objective is to determine long-term flow rates and to establish changes in flows resulting from blast loading. Many persons have lamented the use of continuum analyses which fail to account for discrete flows. The water conducting fissures are unpredictable in extent, orientation, location, and aperture. Tunnelling through an unexpected perched tableor lateral compartment boundary will send water gushing into a tunnel face. But we have to keep in mind the objective of the conference; predicting the long term, or "residual", flows into a sealed base. The fractures might be categorized into two groups; interconnected fractures, and isolated fractures. When performing an injection or pumping test, only the interconnected system generally responds to the test variable. Even interconnected fractures not intersected by the borehole will influence the pumping tests in some fashion. Since the isolated fractures are not connected to the groundwater flow system, they will not play a role in determining the test results.

This feature is relevant to the prediction of flow into an underground excavation in that we are interested in long-term flow, not transient flow as the tunnel is being constructed. In the long term, all of the isolated fractures will become drained, releasing a finite volume of water into the excavation. All of the interconnected fractures will continue to drain into the excavation at a rate of drainage dependent on the mass transmissivity and the groundwater recharge. The groundwater could be recharged by a nearby stream, lake, meoting snow or rain. The mass transmissivity obtained from the pumping tests is just what is required to determine the long-term flow rates. The transient flows encountered during construction (as long as they don't endanger the excavation during construction) are not relevant.

The borehole from which the tests are performed could be considered to be a model of the tunnel. In light of this, the borehole could only be expected to intersect fewer interconnected fractures than the full size excavation, thus the pumping test results could be directly scaled, as a function of the final excavation diameter to the borehole diameter, to arrive at an estimate of the actual long-term flow rate. One of the statistical questions still remains; what about intersecting a flow channel. The statement above is based on uniform fracture flow and may be invalid for channelized flow.

An important research need is to perform a study comparing solutions of flow through homogeneous materials to discrete fracture flow analyses and model tests. Through such a program, some statement could be made addressing the applicability of homogeneous flow solutions to real discrete flow problems. One should also be able to assess the applicability of the fracture flow models.

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APPENDIX B
PAPERS AND REPORTS

This appendix is intended to hold the reports submitted for inclusion in this symposium. The reports will not be included with this report of the Proceedings. If you wish to receive the set of reports, contact:

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They will be supplied at the cost of reproduction and mailing. An alphabetized list (by first author) of the papers included in this appendix follows:

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13. ABSTRACT *(Maximum 200 words)*

At the time of this conference, a deep underground base was a viable alternative for basing strategic defense systems. Among many of the questions that needed to be considered in establishing the suitability of such a basing system was how water would impact the survivability of the base. A hypothetical geology was proposed (Generic Mountain "C") which was analyzed by a number of private companies and individuals. A consensus was generally reached that the model contained inconsistencies, thus leading to several revisions. Although analyses of water flow were done, there seemed to be little confidence in their estimates and it became evident to practical tunnelers that a closer look at predictive techniques was required.

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